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Determination of Fatigue Category and Numerical Analysis of the Stringer to Crossbeam Connection of Riveted Steel Railway Bridges

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Abstract

Fatigue resistance of riveted steel railway bridges, built in the late 19th century and the first half of the 20th century, represents one of the problems affecting their remaining lifetime. The connection of riveted stringer to crossbeam of steel railway bridges with open decks represents a typical fatigue prone detail of these bridges. This structural detail is characterized by the frequent occurrence of fatigue cracks in the stringer web. The standard fatigue assessment method according to Eurocode EN 1993-1-9 is based on categorization of the structural details. When the detail category is known, the fatigue assessment may be done using the appropriate S-N curve, which relates the fatigue life of the detail to the stress range caused by variable load. However, the categorization of riveted details in the standard mentioned above is not sufficient for practical fatigue assessment. In order to define the fatigue category of this detail more properly, the laboratory tests on specially adapted specimens were performed. The paper deals with laboratory investigation of the riveted connection of stringer to crossbeam and numerical simulation of this structural detail using FEM software.

Keywords: fatigue category; numerical analysis, stringer, riveted connection, railway bridges.

1. Introduction

The riveted connection of stringer to crossbeam of railway bridges with open bridge deck is a typical detail prone to a fatigue crack appearance. Webs of stringer and crossbeam are only connected, without flange mutual connecting. Due to the connection arrangement and its certain bending stiffness, the bending moment is arising and producing normal stresses causing the crack in the form given in Fig. 1. However, in the case of the mentioned type of connection, the fatigue detail categorization is absent in EN 1993-1-9 [1]. Therefore, the

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laboratory tests of the riveted detail were realized at the Department of structures and bridges to obtain the fatigue resistance of this structural detail and to define its fatigue category.

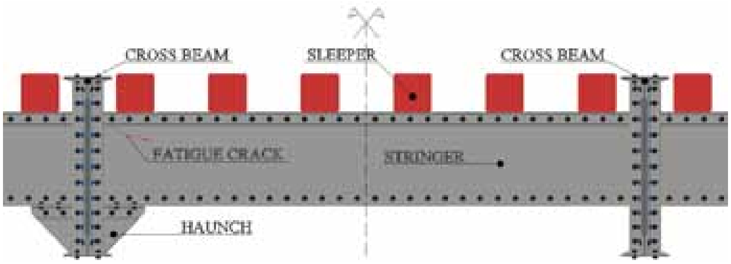

Fig. 1. Fatigue crack and arrangement of a typical stringer to cross beam connection with/without reinforcing haunches

2. Laboratory testing process and experimental results

Configuration of the three types of the laboratory specimens can be seen in Fig. 2. The specimens of type I and II were tested in 2009 and the testing process, as well as the test results, was described in [2]. Other five specimens were tested in the laboratory of Transport Research Institute in Žilina in 2010. The more detail description of the testing process of specimens of type III was published in [3].

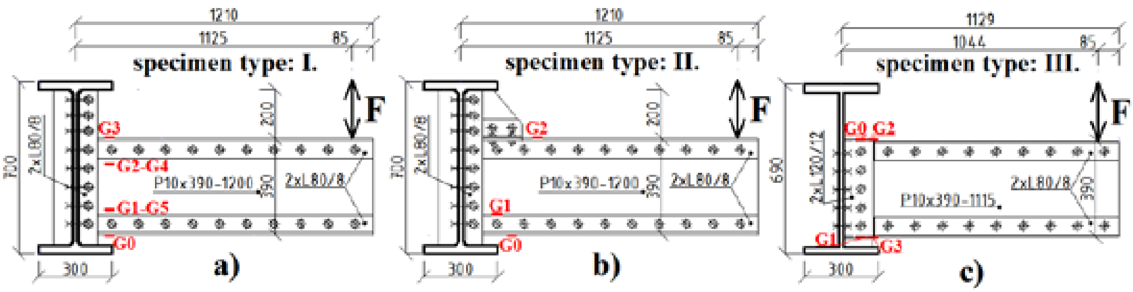

Fig. 2. Configuration of laboratory specimens without haunch (I), reinforced by haunch (II), new specimens without haunch (III) and specimen gauge arrangement

All the specimens were gradually subjected to fluctuating bending moment through the application of concentrated vertical load. For all the specimens, the loading forces were alternating between positive and negative limit values (see Fig. 2). At the start of fatigue test, each specimen was loaded statically at the maximum and minimum values of the loads that would be applied during the fatigue test. Normal stresses in the stringer web were measured by means of gauges LY11-6/120 [4]. Location of gauges is shown in Fig. 2. Measured data was recorded by measuring equipment Spider 8, controlled by computer software Catman. For more detail see [3].

Typical failures of the investigated detail are presented in Fig. 3. Picture on the left shows the out-of-roundness failure of the rivet hole due to the material cyclic plasticisation, after which the global beam deflection is rapidly growing. The picture on the right shows the classic type of fatigue failure in the form of crack starting from the rivet hole.

Fig. 3. Types of fatigue failures of the detail

Based on the regressive analysis results, the fatigue resistance of investigated detail corresponding to $2 \cdot 10^6$ cycles is $\Delta\sigma_C$ = 83.9 MPa. Therefore, the detail can be classified to the category 80 according to EN 1993-1-9 [1], i.e. $\Delta\sigma_C$ = 80 MPa.

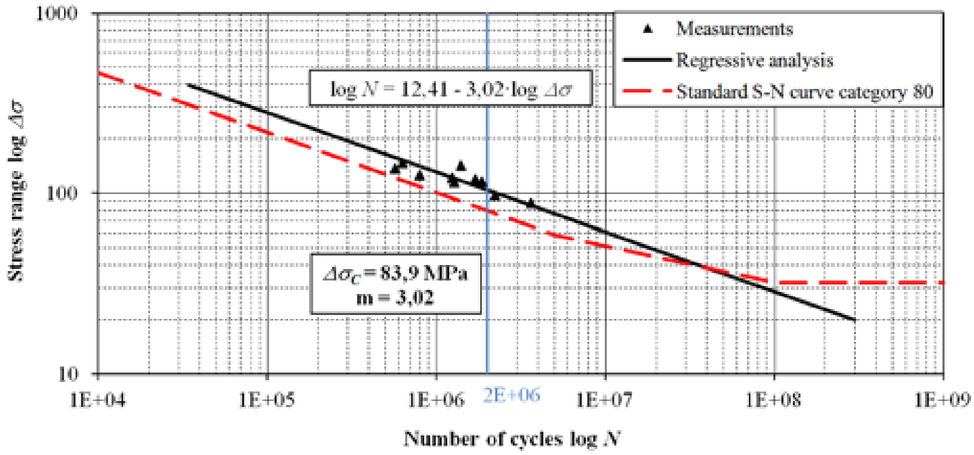

Fig. 4. Results of fatigue tests

3. Description of the numerical model

Several computational models were developed before and after the fatigue tests, using the SCIA Engineer 2009 software and, subsequently, the ANSYS Workbench v12. The description of the models, obtained results and their comparison, as well, were published in [3]. The simplified model of the riveted stringer specimen (see Fig. 5) was created in the ANSYS software. Based on the comparison of numerical results with experimental results, this model seemed not to be adequate enough. Therefore, the more complex and complete model was necessary to create using the ANSYS, see Fig. 6. But, developing an accurate computational model describing the real behaviour of the tested specimens was a very complicated task.

There were a several sub-problems within creation of the complete model. The first problem was modelling of the behaviour of contacts between the stringer web and vertical and horizontal angles. To determine the area of the rivet shank in contact with the area of rivet hole was the second one. Another challenge was to determine the prestressing forces in the rivets due to the technology of the connection assembly.

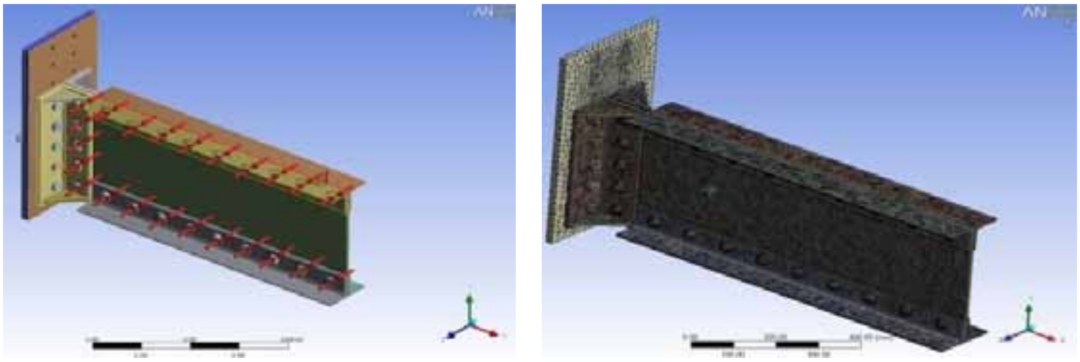

Fig. 5. First preliminary model of specimen with prestressing forces in rivets

The basic task was to calibrate the applied model in such a way to obtain numerical results in relatively good compliance with the stress records obtained by means of particular strain gauges. Another question was which results of experimental analysis should be taken into account in comparison to the numerical ones, i.e the results from the first start of specimen testing or results obtained by the measurement of strain using particular gauges during pulsation of specimen. Finally, the first option was chosen.

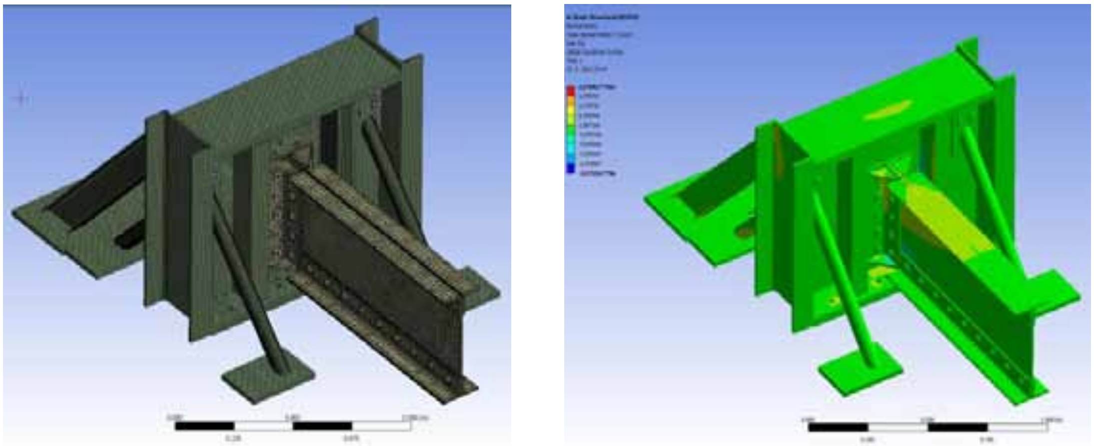

Fig. 6. a) FEM model in ANSYS Workbench and mesh of finite element b) Normal stresses in the specimen caused by pulsating forces

The behaviour of specimen during the pulsation was the main reasons for this choice. The friction between stringer web and angles and also the prestressing forces in rivets were successively disappearing in the individual contacts by each cycle due to the gradual out-of-roundness of the hole diameter caused by the material cyclic plasticisation.

Therefore, the specimen changed their stiffness during pulsation. Modelling the change of the connection stiffness during pulsation in the computational model was very complicated. In the simplified numerical specimen model, the friction was considered in the problem contacts. The coefficient of sliding friction on the steel-to-steel contact was considered within the range of 0.2 - 0.3. Based on the study [5], the prestressing forces were modelled in the rivets situated in vertical angles only (see Fig. 5 on the left). The simplified model showed an excessive deformation and unstable behaviour in the transversal and also in the longitudinal direction. Therefore, the friction on the rivet shank area in contact with the rivet hole area was neglected. The contact was replaced by the rigid connection and the prestressing force was not taken into account. Thus, the final model, assuming the friction on the contact between angles and the stringer web, was obtained to analyse the stringer to crossbeam connection more realistically.

The numerical model was developed using the finite element Solid 185, which was considered for modelling of stringer, crossbeam, bolts and rivets, respectively. This element is defined by eight nodes and orthotropic material properties are assumed. Basic material characteristics (mean values) of stringer and crossbeam were obtained by testing - the yield strength f_y = 244.92 MPa, the ultimate strength f_u = 360.77 MPa, Young's modulus E = 210 000 MPa and Poisson ratio ν = 0.3. The material properties corresponding to the steel 11 343 were used for rivets. The yield strength f_{yb} = 640 MPa and the ultimate strength f_u = 800 MPa were considered for bolts of strength class 8.8, which were connecting the vertical stringer angels to the crossbeam web. The values of friction coefficient 0.15, 0.175, 0.200, 0.225, 0.300 and 0.400 were considered in the parametric study to analyse the real behaviour of the investigated connection.

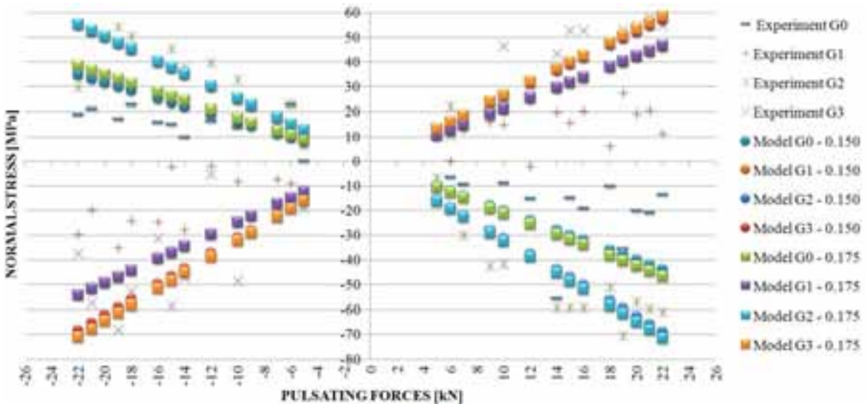

Fig. 8. Experimental and parametric study results with friction coefficient of 0.15 and 0.175

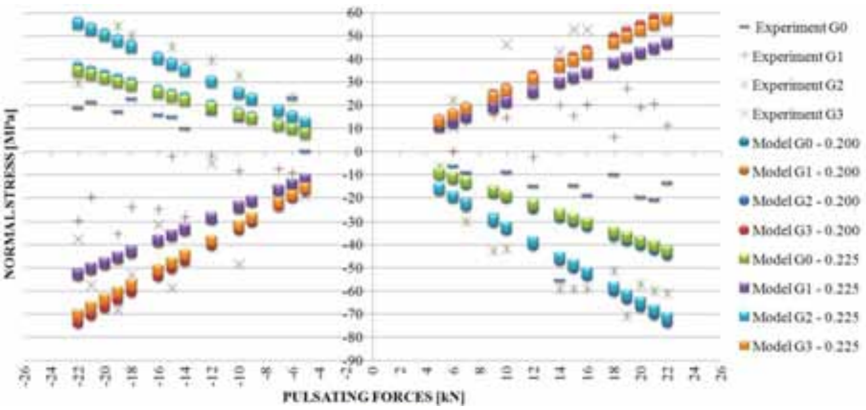

Fig. 9. Experimental and parametric study results with the friction coefficient of 0.200 and 0.225

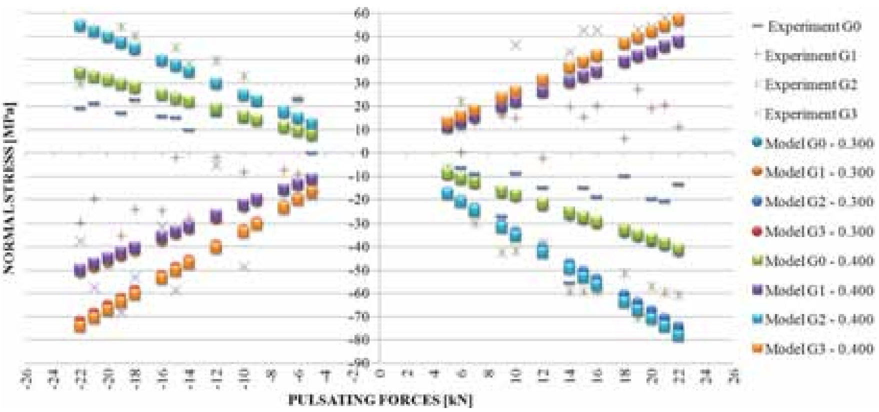

Fig. 10. Experimental and parametric study results with the friction coefficient of 0.300 and 0.400

4. Conclusion

The aim of the parametric study, presented in this paper, was to obtain and to calibrate the more sophisticated computational model of the stringer to crossbeam connection typical for railway bridges with open bridge decks, using ANSYS Workbench. Determination of the adequate friction coefficient substituting the prestressing forces in rivets and simplification of the numerical model is introduced. The normal stresses of numerical model mentioned above should be in compliance with the experimental results. Comparison of the parametric study results with the experimentally measured stresses using strain gauges are shown in Fig 8 – Fig. 10. As can be seen, the numerical model using friction coefficient 0.400 seems to be the most appropriate one. The calibration of the computational model was necessary to prepare for implementation of the fatigue analysis by means of software ANSYS to describe the stringer to crossbeam connection behaviour and to explain the reasons of crack arise and development.

Acknowledgement

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